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Report No. FAA-RD 78-54

(18) (19)

FOR FURTHER TRAN

(6) DESIGN OF AN APPARATUS FOR TESTING
THE FLAMMABILITY OF FUEL SPRAYS.

(10) Thor I. Eklund
and
William E. Neese

(14) FAA-NA-78-6

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286. Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	36	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

Temperature scale:
°F: -40, 0, 32, 98.6, 200, 212
°C: -40, -20, 0, 20, 37, 40, 60, 80, 100

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15. Supplementary Notes

16. Abstract

An automated small-scale test apparatus was developed for flammability testing of modified fuels. The test configuration consists of a 1/4 inch fuel delivery tube within a 1 inch air atomization pipe followed by a diffuser section. A pressurized 30 gallon air tank supplies the atomization air while a syringe pump provides a specified fuel quantity for all tests. Isentropic calculations and hot wire anemometer measurements characterize the air flow during the transient air release. Oscillograph traces specify the sequencing and timing of events. It is concluded that this transient test is a practical device for modified fuel testing because of its simple construction, well-defined operation, and capability of distinguishing between candidate additives.

17. Key Words Flammability Turbine Fuels Antimisting Fuels Ignition Modified Fuel Test Apparatus	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22151

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INTRODUCTION

PURPOSE.

The purpose of this project was the development of a small-scale test apparatus for the comparison of the flammability of modified fuel sprays.

BACKGROUND.

Two practical problems have hindered attempts to develop antimisting fuels and to correlate results of tests at different laboratories. One problem has been the lack of simple rheological tests to measure additive effectiveness from a fluid flow perspective. The other problem has been the lack of a widely accepted spray flammability test that could be used for screening and evaluating prospective antimisting fuels.

The rheological characteristics of a number of additives have been comprehensively described (reference 1), but more work is required to demonstrate that any one test could indicate the effectiveness of an additive. Such tests are essential to ensure that identical additives tested at different installations are the same in their fluid properties. Past experience has shown that the molecular weight distribution and possibly the structure of the additive macromolecules are susceptible to change through mixing, pumping, and aging.

With regard to spray flammability, a wide variety of tests had been used for antimisting fuels (reference 2). The majority of these tests had been large-scale and unique to a particular laboratory. The most realistic tests clearly show the crucial effect of airspeed on antimisting fuel flammability (reference 3). Nevertheless, except for the "mist flashback technique" (reference 4), no small-scale techniques are available to evaluate antimisting fuels. The large droplet size and nonspherical geometries involved in antimisting fuel sprays have been documented previously (reference 5). The feasibility of reproducing the droplet geometries on a small scale has also been demonstrated (reference 6).

In general, laboratory scale experiments used in scientific studies of spray combustion are too small to accommodate the particle sizes produced by antimisting fuels. Any small-scale test would have as its main requirement the production of coarse sprays similar to those documented in larger-scale tests.

EXPERIMENTAL OBJECTIVE.

The experimental objective was to develop a small-scale spray flammability test that would create spray geometries observed in larger-scale tests and be inexpensive to fabricate. The small-scale test should be adequate for screening and evaluating antimisting fuel candidates, and be self-contained so that neither extensive nor specialized facilities would be required for use.

1

DISCUSSION

TEST APPARATUS.

The test configuration was based on earlier developmental work in a fuel spray photographic chamber (reference 6). The atomization technique involves injection of fuel through a 1/4-inch tube concentric and concurrent with a high-velocity airstream in a 1-inch pipe. The fuel and air mixture is then diffused through a cone to a lower velocity. Downstream of the cone, the mixture is passed over a propane torch igniter. The airflow from the apparatus is at a decreasing but specified rate, due to a sonic orifice in the 1-inch pipe. The air is supplied from a pressurized 30-gallon tank. The fuel flow is a known constant rate as supplied by a syringe pump with a screw-type drive. In the test, a fuel that is finely atomized will readily burn at the propane torch. However, an antimisting fuel will not burn when its rheological behavior minimizes the degree of atomization from the airstream.

Figure 1 shows an overall view of the complete test apparatus. Facility air is used to pressurize the air tank, and an auxiliary propane tank supplies the igniter torch. Figure 2 shows the breadboard test apparatus final to packaging. Included in the illustration are the air supply tank (DeVilbiss Type TA-470), the air control solenoid (Atkomatic No. 600), the orifice flange, the air pipe, and the diffuser cone. On the table is the timer (Industrial Timer, model RC-1) which controls the test sequence automatically. Also visible in figure 2 is the fuel pump assembly. Figure 3 shows the complete fuel pump and screw motor. Design details are found in appendix B.

A top view of the assembled test is shown in figure 4 and a side view in figure 5. The control switches and lights are visible in the top view, while the wiring and plumbing are evident in the side view. The side panels, wiring, and the plumbing are shown in figures 4 and 5. The essential features of the test device are the breadboard components of figure 2. These essential features are detailed in figures 6 and 7. Figure 6 shows a schematic of the air supply system and details the 0.25-inch sonic orifice construction and identifies the components by manufacturer. Figure 7 details the fuel delivery system, the diffuser, and the ignition assembly, and the relevant callouts are identified in the legend. The electrical circuit which controls the test is found in appendix B.

The air and fuel system, as controlled by the timer, provide a well defined and repeatable test for the antimisting additives.

OPERATION.

The test apparatus can safely be operated in a laboratory or shop area. No safety devices other than a hand-held CO_2 extinguisher are required, since the quantities of fuel tested are small. Indoor operation allows temperatures to be consistently maintained at approximately 68° Fahrenheit (F) and prevents winds and drafts from affecting the spray flow at the diffuser exit.

In the test procedure, the air tank is pressurized to approximately 100 pounds per square inch gauge (psig) from either facility air or a small compressor. The operator will flush the fuel cylinder three times with the fuel to be tested. This eliminates the residue from previous tests. A retract switch and extend switch on the control panel allow the operator to override the timer circuit for the flushing operation.

The test is initiated by a sequencer switch and occurs automatically. The order of the operations, along with the time from start, is as follows:

1. Sequence switch activated, 0.0 second
2. Igniter spark turned on, 1.5 seconds
3. Propane turned on, 3.4 seconds
4. Air turned on, 5.0 seconds
5. Fuel turned on, 5.8 seconds
6. Igniter spark turned off, 6.9 seconds
7. Fuel turned off, 9.5 seconds
8. Propane stops, 10.7 seconds
9. Air stops, 10.9 seconds

An oscillograph trace of the process is shown in figure 8. Identified on the trace are noise spikes which mark the events as well as continuous traces for the tank pressure drop, the air pipe temperature, a hot-wire anemometer in the air pipe, and the fuel pump motor. The latter trace was used to more clearly identify the time at which fuel delivery started and the time that it stopped. Appendix A includes detailed isentropic calculations for the airflow along with the velocity measurements from the hot wire. The agreement between the calculations and measurements is satisfactory. The measurements define an initial peak centerline air velocity in the pipe at over 280 feet per second (ft/s). The velocity drops nearly linearly during the test to approximately 210 ft/s. Thus the sample fuel is initially sheared by a high velocity air-stream in the pipe. The fuel and air then decelerate as they pass through the cone.

The total fuel flow during a test was measured at 37 cubic centimeters (cc). Some of the tests showed fuel loss from the spray through dripping from the diffuser mouth during or after the test. Two fuels, Conoco AM-1 and Imperial Chemical Industries FM-4, showed no dripping at all. These are fuels characterized by high tensile viscosities. Neat Jet A lost 5 cc to dripping during the test and 3 cc to dripping immediately after the test. This represented a total loss of over 20 percent. Imperial Chemical Industries FM-9 showed no dripping during the test but did show a 6 cc loss immediately after the test. FM-9 is not characterized by a pronounced tensile viscosity. Apparently a high tensile viscosity inhibits the spreading of fuel to the walls of the diffuser. This loss of fuel to to the apparatus walls should be subtracted from the total fuel flow in any determinations of the fuel-air ration of the fuel sprays.

3

FUEL PERFORMANCE.

The fuels tested included Jet A and the antimisting fuels FM-4, AM-1, and
FM-9. For the antimisting fuels, the weight percentages of the additives
in Jet A were 0.4 percent, 0.2 percent, and 0.3 percent respectively. Quali-
tatively, the ignitability behavior was similar to that observed in other
tests (references 5 and 6). Figure 9 shows the fire resulting from ignition
of Jet A. In contrast is the ignition attempt on FM-9 as shown in figure 10.
Both FM-4 and AM-1 showed pronounced lengthening of the flame behind the
torch, but neither showed the lateral flame propagation evidenced by the
Jet A.

The test apparatus has the flexibility to vary operating conditions. Change
in air tank pressure or orifice plate results in a change in air delivery rate.
A change in diameter of the fuel piston pump would change fuel-flow rate.
The configuration and settings described in this report were developed by vary-
ing orifice size and tank operating pressure to get: (1) minimum dripping from
the diffuser, (2) a repeatable Jet A flame, (3) good drop trajectories, and (4)
lengthening of the torch flame with AM-1 and FM-4. For instance, at low air-
flow rates, the AM-1 fuel strands dropped below the propane torch. At
excessively high airflow rates, the Jet A fuel-air ratio began to show lean
fire characteristics, and the FM-4 and AM-1 showed little torch lengthening.
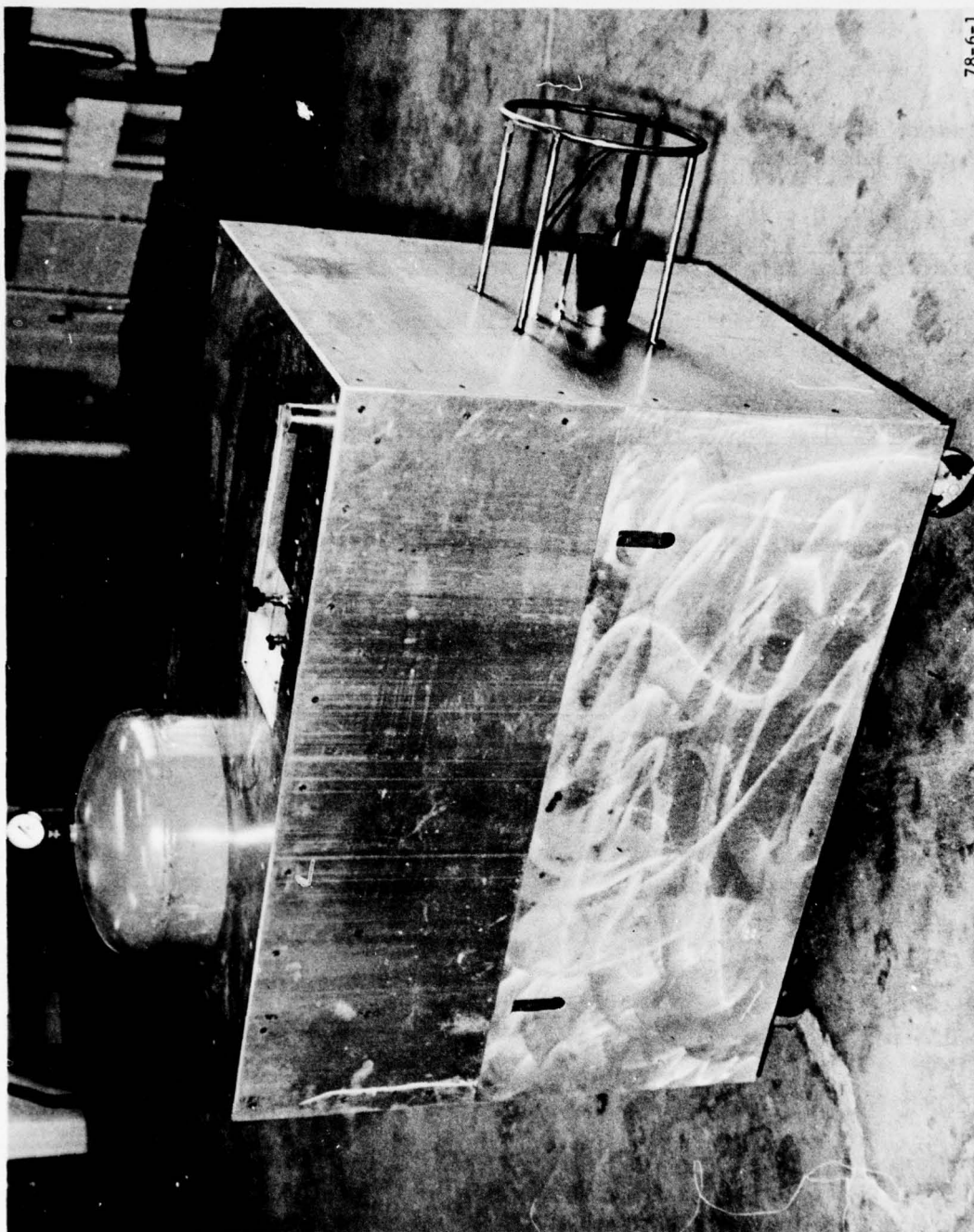

CONCLUSIONS

The design, construction, and evaluation of a small-scale flammability test
lead to two conclusions:

1. A simple and portable flammability test for fuel sprays is feasible.

2. Use of a transient air supply and a timed sequence of test events provides
a well-defined and quantified test environment.

4

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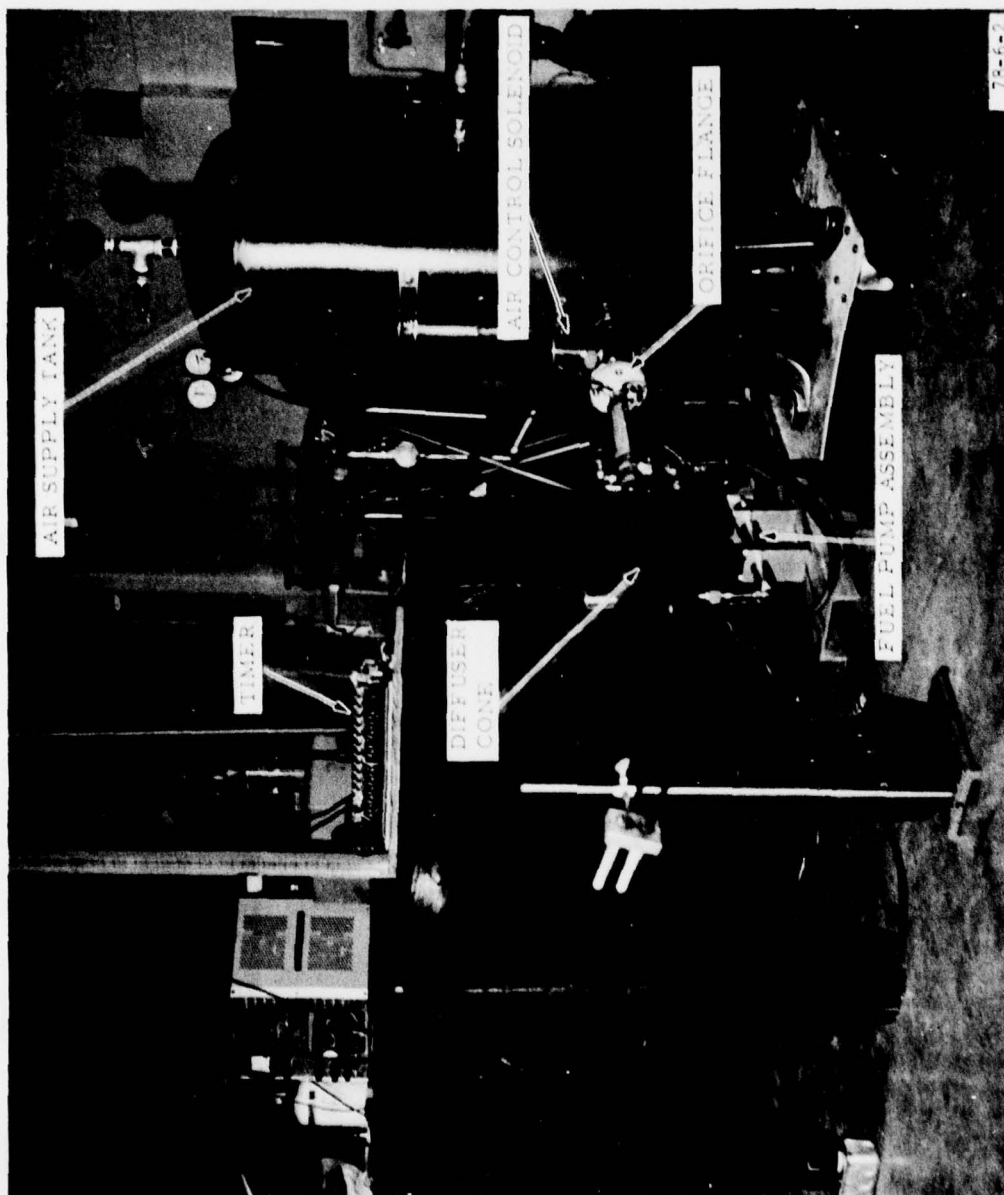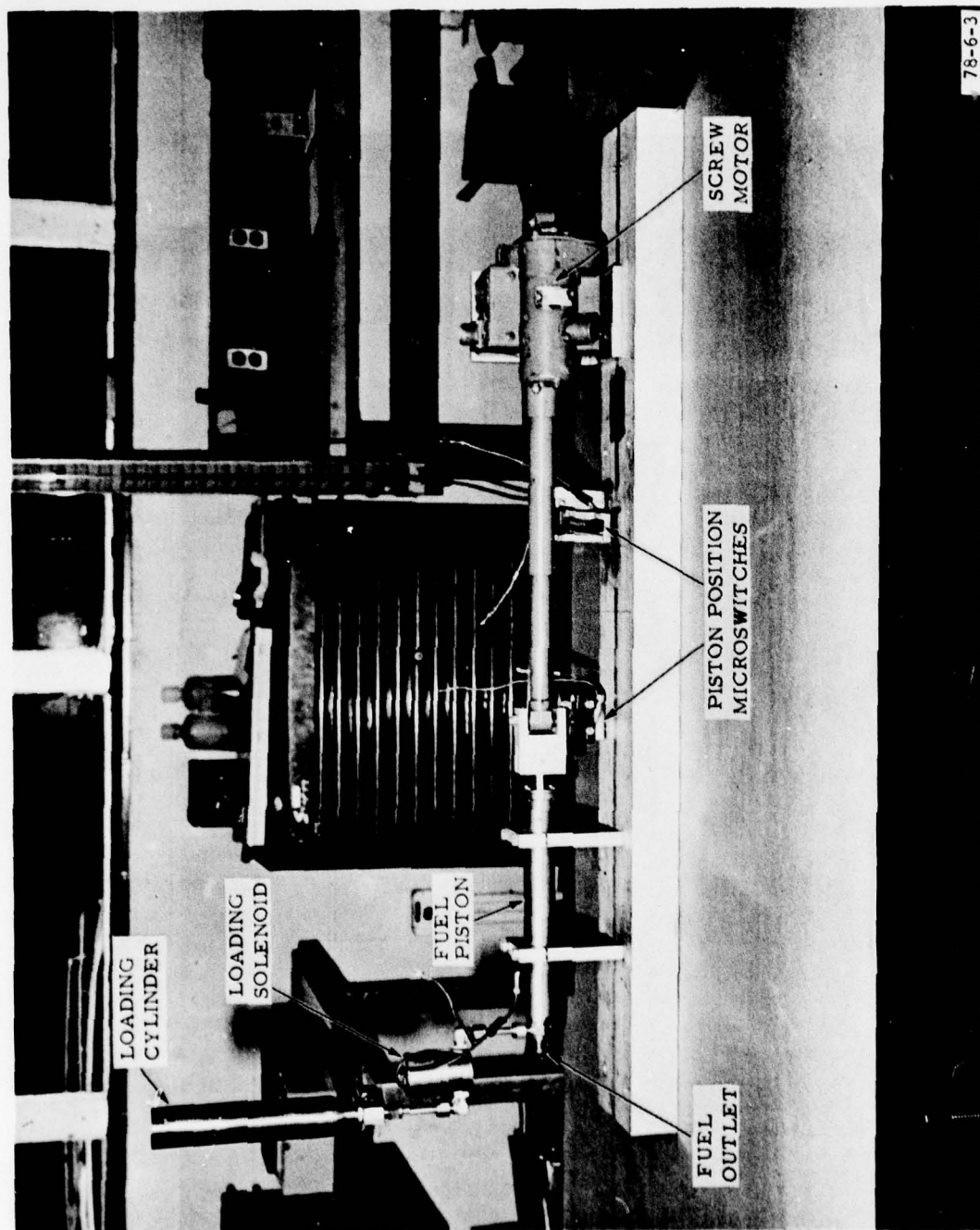
78-6-1

FIGURE 1.   MODIFIED FUEL TEST APPARATUS

6

FIGURE 2.   BREADBOARD ASSEMBLY
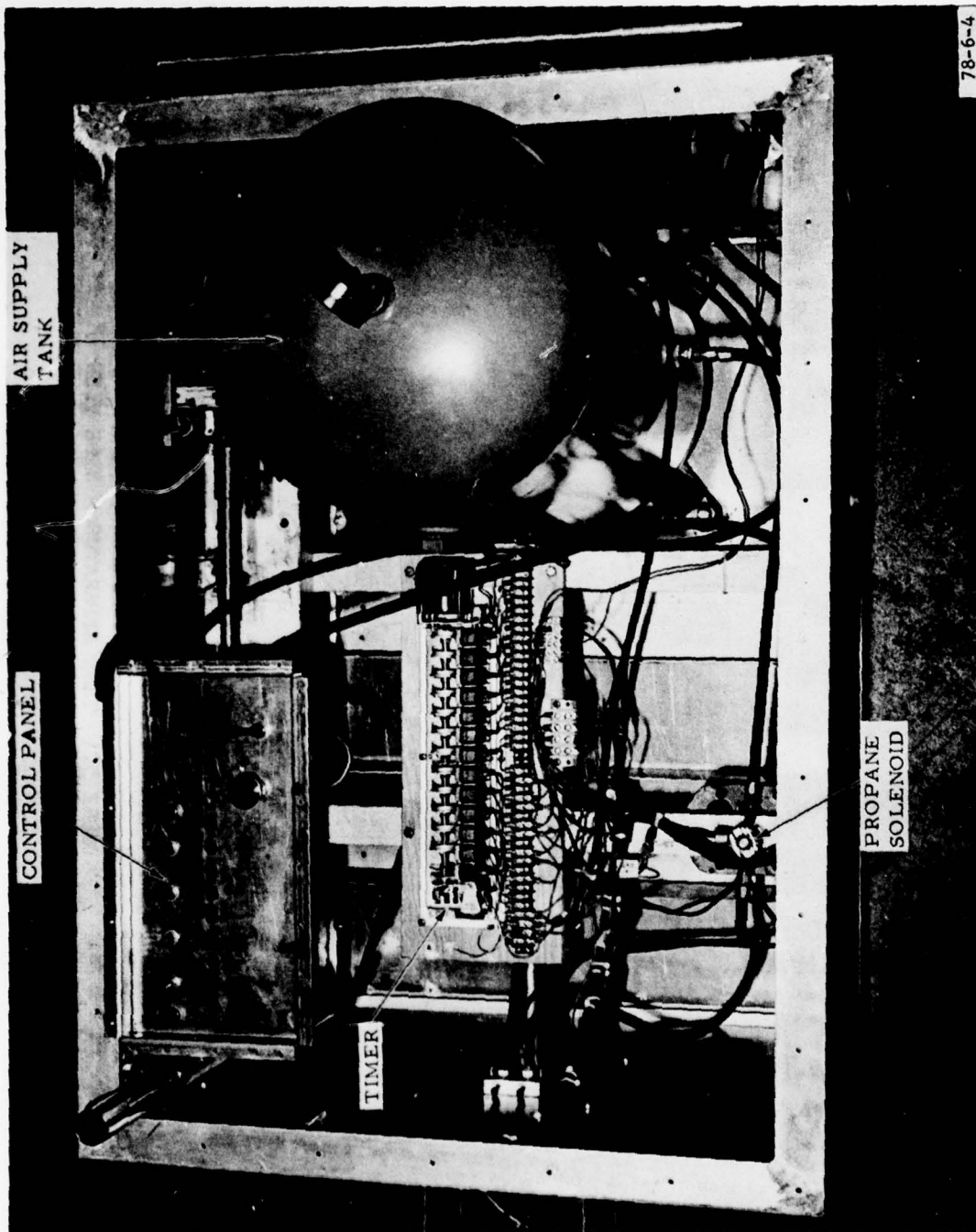
7

78-6-3

FIGURE 3. FUEL PUMP ASSEMBLY

8

AIR SUPPLY
TANK

CONTROL PANEL

PROPANE
SOLENOID

TIMER

78-6-4

FIGURE 4. TEST APPARATUS - TOP VIEW

9
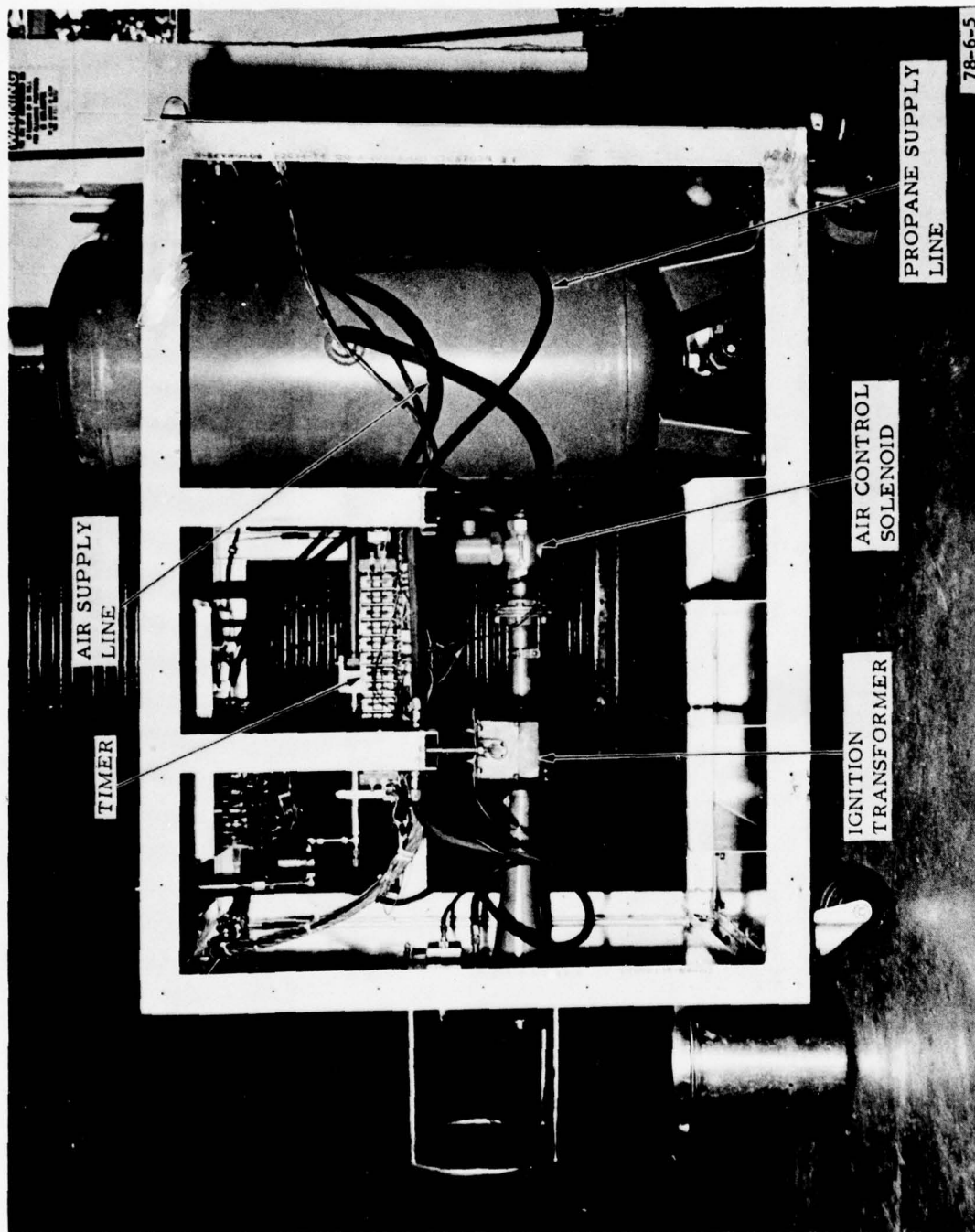
FIGURE 5.   TEST APPARATUS - SIDE VIEW

78-6-5

PROPANE SUPPLY LINE

AIR CONTROL SOLENOID

AIR SUPPLY LINE

TIMER

IGNITION TRANSFORMER

10

BEVEL
118° INC.
ANGLE

FLOW

5/16 " DIA HOLE
4 PLACES

.250" DIA
HOLE

78-6-6
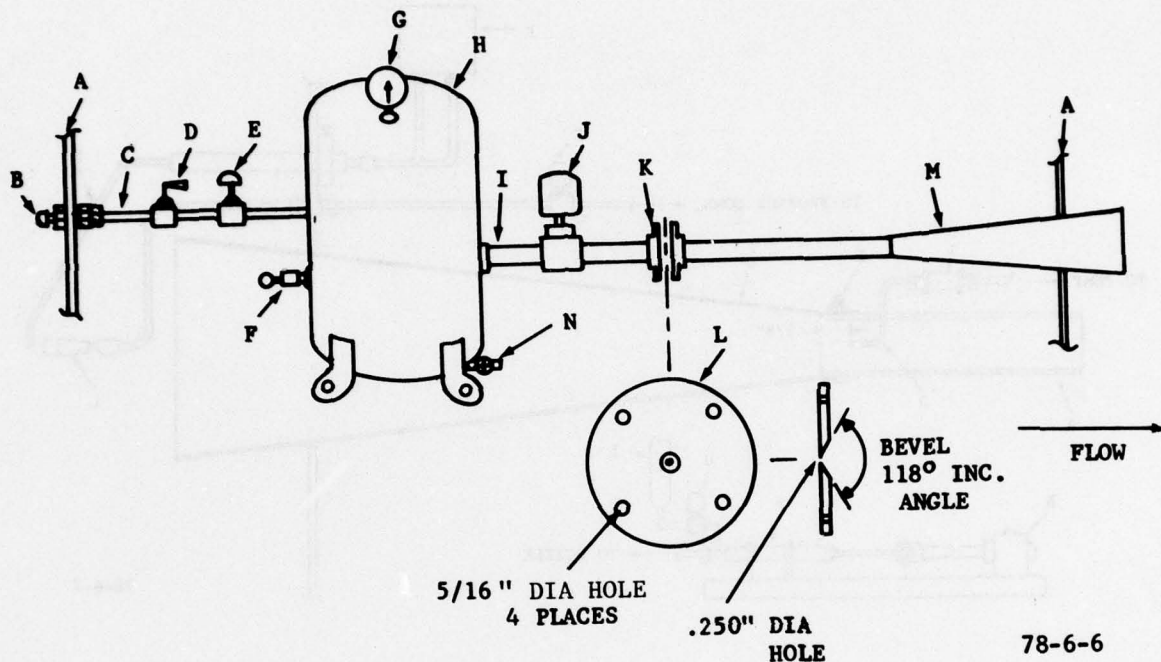
LEGEND

A.   Enclosure, aluminum sheet and angle.
B.   Air hose coupling, Schrader 8050-11.
C.   Copper tube, .250 inches x .032 wall (refrigeration).
D.   Air control valve, toggle (off-on) Whitey 1GS4-SS
E.   Air regulator valve (needle) Whitey 1RS4-SS
F.   Safety valve, DeVilbiss Type TA, ASME Std. 1/4 inch, pressure 165 PSI
G.   Gage pressure, Marsh Instrument Co., 0-160 PSI.
H.   Air storage vessel, DeVilbiss TA-470, 30 gallons.
I.   1 inch, schedule 40 pipe.
J.   Air flow control valve, Atkomatic No. 600 2-way solenoid valve.
K.   1 inch pipe flange (2).
L.   Orifice plate .125 inch T3 aluminum.
M.   Deceleration cone, .018 inch thick steel.
N.   Condensate drain, 1/2 inch-brass valve.

FIGURE 6.   AIR SUPPLY SYSTEM

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78-6-7
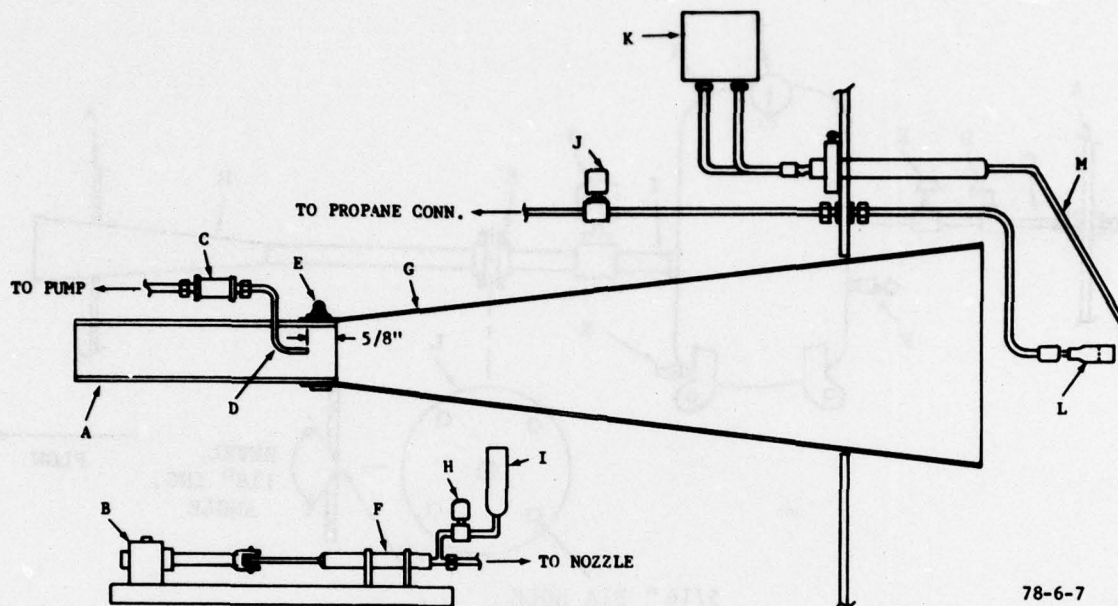
LEGEND

A. Air tube, 1 inch schedule 40 pipe.
B. Linear actuator, Airesearch mod. ELA 8-49-3
C. Check valve, NUPRO SS-4C-1/3
D. Fuel nozzle, open 1/4 inch stainless tube
E. Mount clamp, 1 1/2 inch hose
F. Pump
G. Deceleration cone, 14 3/8 inches long x 4 inches diameter air exit
H. Pump reload solenoid, Skinner V52DA2100
I. Pump reload reservoir
J. Propane control solenoid, Skinner V52DB2022
K. Ignition transformer, type 312-2AABC-202
L. Propane nozzle, Bernzomatic
M. Propane ignition electrodes

FIGURE 7.   FUEL ATOMIZATION SECTION

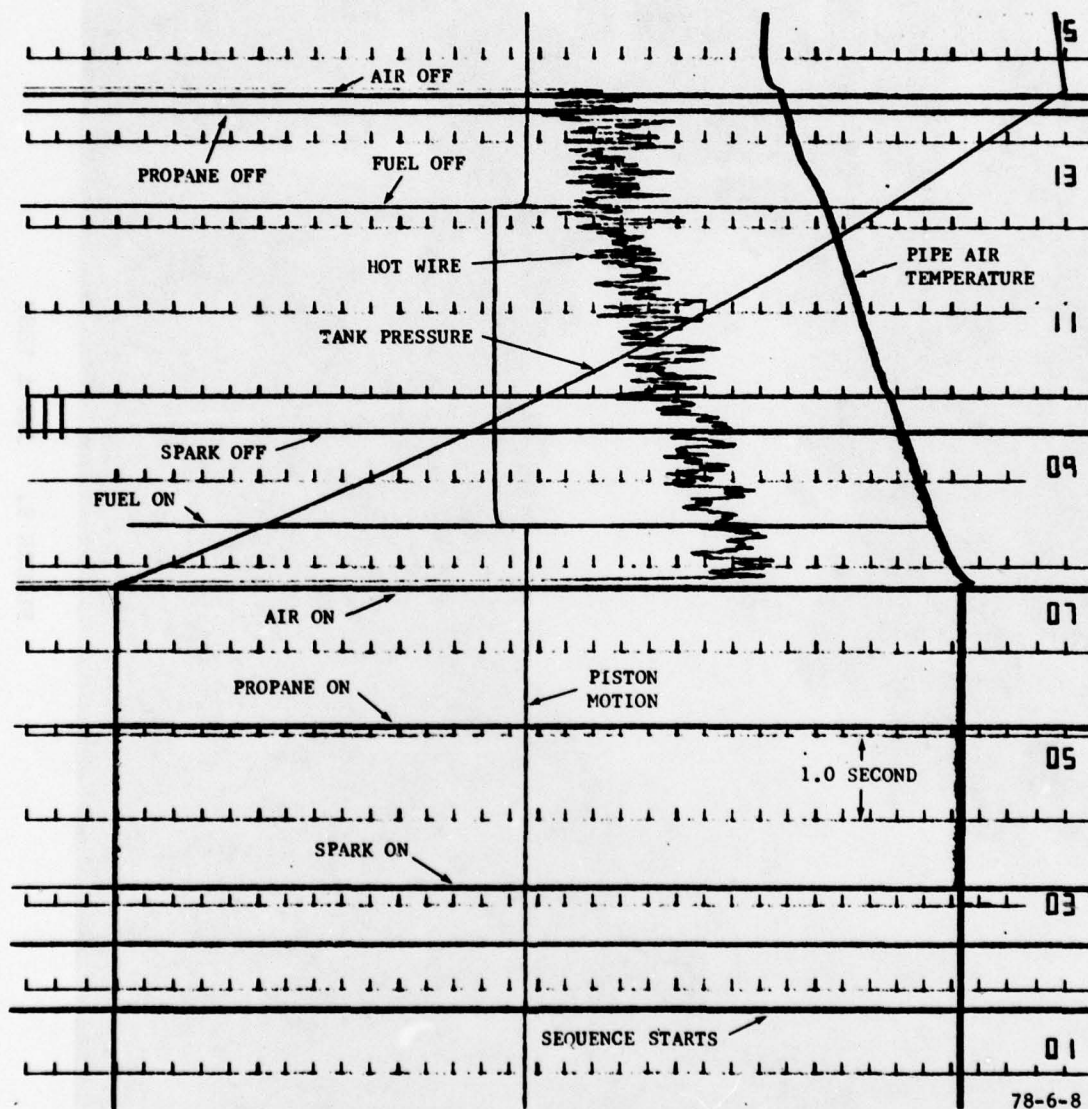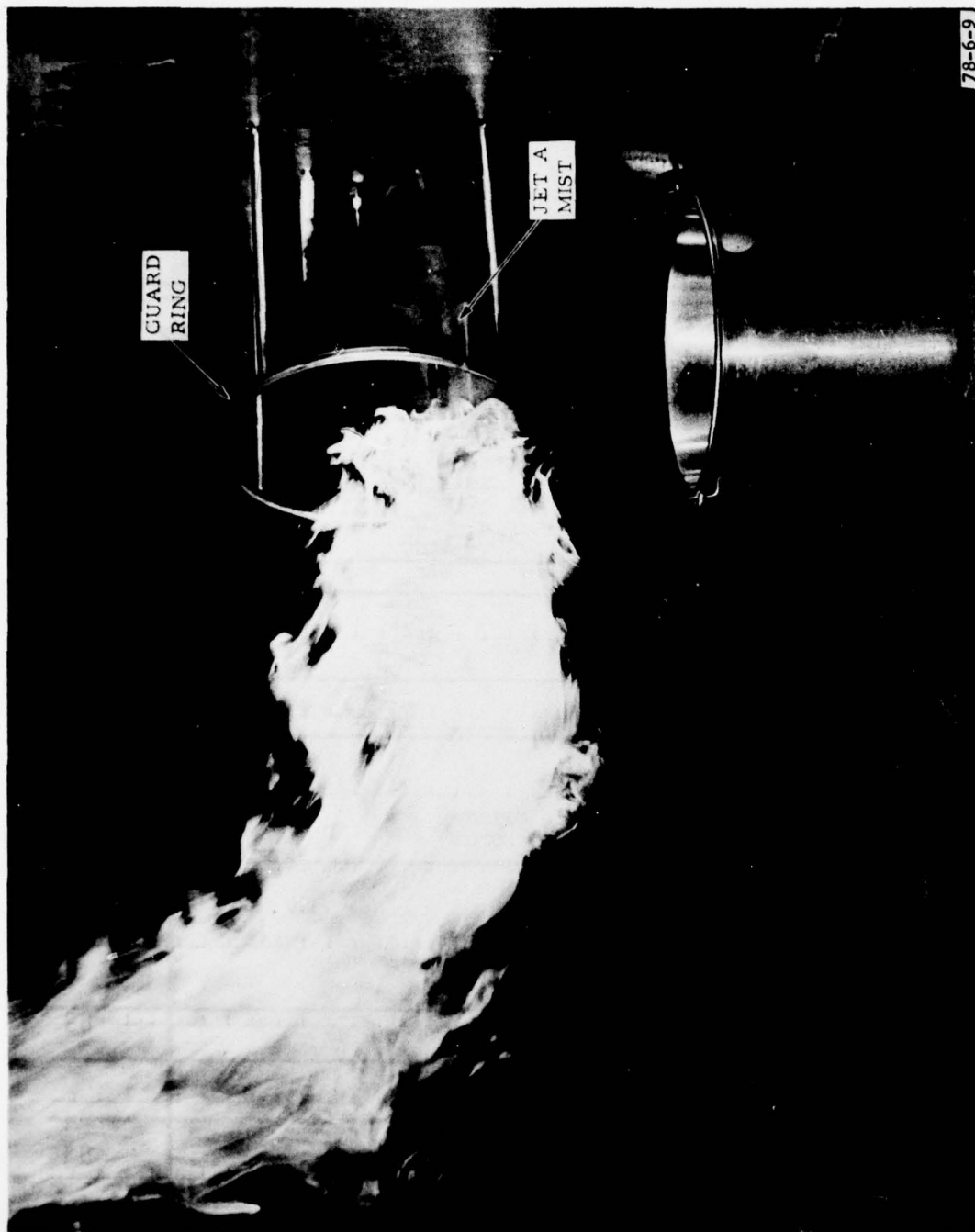12

FIGURE 8.   OSCILLOGRAPH RECORD

13

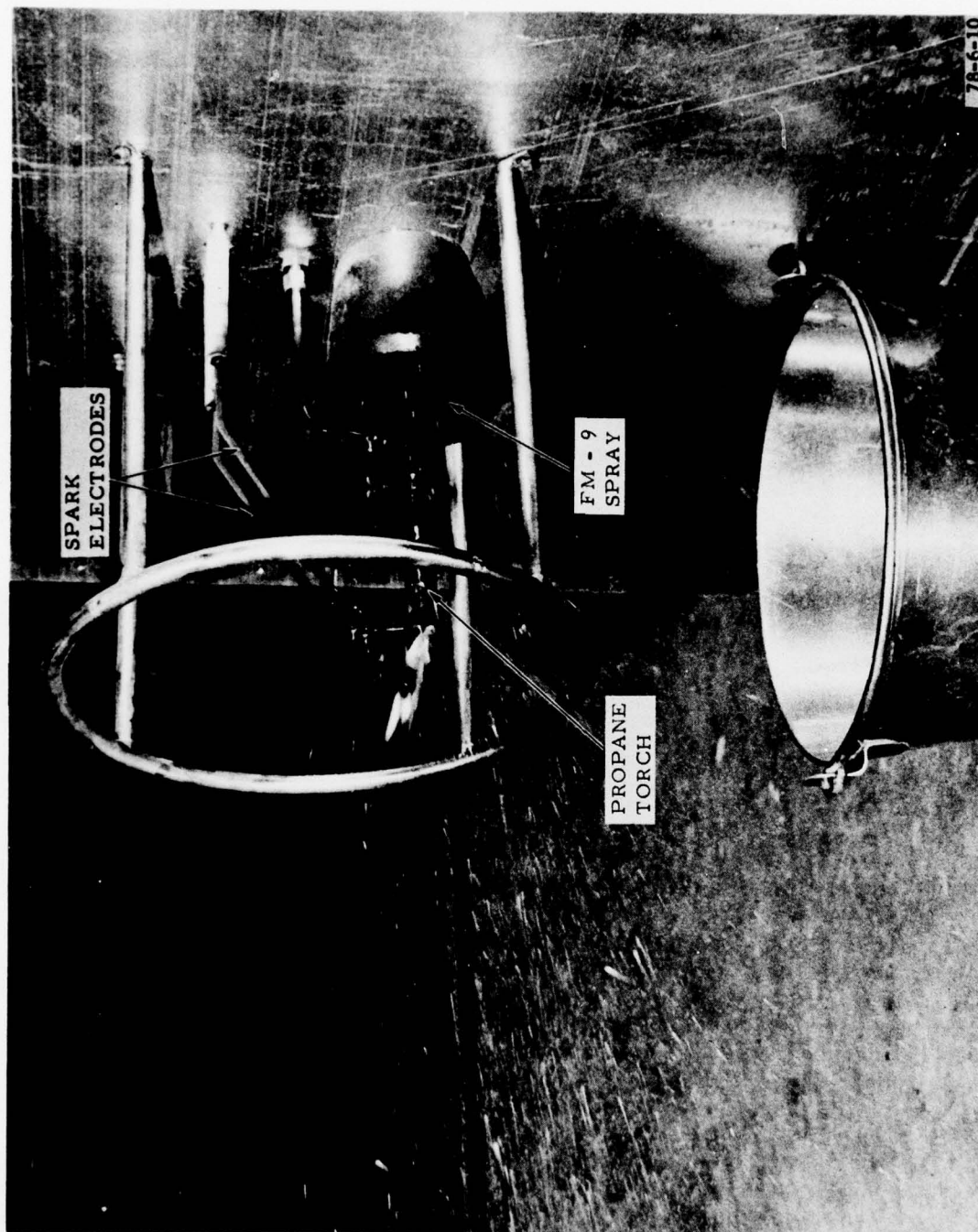78-6-9

GUARD RING

JET A MIST

FIGURE 9.   JET A TEST

14

FIGURE 10.   FM-9 TEST

15

FLOW DIAGNOSIS

The pertinent air-flow parameters can be readily computed from the isentropic gas laws. The atomization air is supplied from the 30 gallon tank through a 0.25 inch sonic orifice. The mass flow rate through the orifice is found from Fliegner's formula (reference 7):

$$w = 0.532 \; p_o \; A^*/\sqrt{T_o} \qquad (A-1)$$

where p_o is the tank air pressure in pounds force per foot squared (lbf/ft^2), A^* is the effective orifice area in ft^2, and T_o is the tank air temperature in degrees Rankine (°R). The flow rate, w, is in pounds mass per second (lbm/s), and to maintain correct dimensions, the constant 0.532 is in units lbm $\sqrt{°R}/lbf/s$.

Since the amount of gas in the tank decreases as a test proceeds, the quantities p_o and T_o in equation (A-1) are functions of time. A mass balance on the tank results in:

$$\rho_i \; V - \int w \; dt = \rho_o \; V \qquad (A-2)$$

where ρ_i is the initial air density in the tank, t is time, ρ_o is the instantaneous density in the tank, and V is the tank volume. For manipulation of equations (A-1) and (A-2), the isentropic laws will be used to replace p_o and T_o with $_o$ and the initial conditions. Using (A-1),

$$\frac{p_o}{p_i} = \left(\frac{\rho_o}{\rho_i}\right)^\sigma \qquad (A-3)$$

and

$$\frac{T_o}{T_i} = \left(\frac{\rho_o}{\rho_i}\right)^{\sigma-1} \qquad (A-4)$$

where σ is the specific heat ratio of 1.4, equation (A-2) can be rewritten as:

$$\rho_o = \rho_i - \int \frac{0.532 \; p_i \; \rho_o^{\frac{\sigma+1}{2}} \; A^*}{T_i^{\frac{1}{2}} \; V\rho_i^{\frac{\sigma+1}{2}}} \; dt \qquad (A-5)$$

At this point, density will be normalized by dividing with the initial density to form the quantity ρ^*. With this substitution, equation (A-5) will be differentiated to form:

$$\frac{d\rho^*}{dt} = \frac{-0.532 \; p_i \; A^*}{T_i^{\frac{1}{2}} \; V\rho_i} \; \left(\rho^*\right)^{\frac{\sigma+1}{2}} \qquad (A-6)$$

This expression can be integrated after suitable rearrangement to form:

$$\rho^{*\frac{1-\sigma}{2}} = \left[\left(\frac{\sigma-1}{2}\right) \left(\frac{0.532 \; p_i \; A^* t}{T_i^{\frac{1}{2}} \; V\rho_i}\right)\right] +C \qquad (A-7)$$

where C is an integration constant. Since $\rho*$ is unity when $t = 0$, C simply comes out to be unity. Once $\rho*$ is found as a function of time, the temperature and pressure in the tank can be found from the isentropic relations. The calculation should be good until the tank pressure gets down to around 15 psig. Table A-1 presents calculated tank pressure and orifice mass flow for an initial tank pressure of 114.3 pounds per square inch absolute (psia) and initial tank temperature of 525°R. The effective area was found by multiplying the nominal orifice area by a factor of 0.85 to include an orifice discharge coefficient in the calculation (reference 7). Also included are calculated tank temperatures. Figure A-1 shows a plot of both the measured and calculated pressures as a function of time. The pressure was monitored with a 0 to 100 psig transducer (Teledyne Model 217-5A) and recorded on a recording oscillograph (Honeywell Model 1885A strain gauge control and Model 1858 CRT Visicorder). The close agreement indicates that the isentropic calculations provide accurate values for total flow quantities.

TABLE A-1.   FLOW CALCULATIONS

Time (s)	Calculated Tank Pressure (psia)	Calculated Air Flow (lbm/sec)	Calculated Tank Temperature (°R)	Calculated Mean Velocity (ft/sec)	Measured Pipe Temperature (°R)
5.0	114.3	.1107	525.0	268	525
6.0	107.0	.1047	515.1	253	523
7.0	100.2	.0989	505.5	237	519
8.0	93.8	.0935	496.2	222	515
9.0	88.0	.0885	487.2	209	511
10.0	82.5	.0837	478.3	196	508

NOTE: t = 5.0 marks the time at which the air valve opens.

Additional calculations were made to find the mean air velocity in the 1-inch pipe from the continuity equation:

$$w = \rho V A \tag{A-8}$$

where ρ is the air density in pound mass per cubic foot (lbm/ft^3), A is the pipe cross-sectional area in ft^2, and V is the air velocity in ft/s. The flow rate, w, is found from equation (A-1), the area is known, and the density is found from the perfect gas law:

$$p = \rho RT \tag{A-9}$$

A-2

The pressure is assumed to be 14.7 psia and the temperature is an experiment-
ally measured temperature taken with a 1/16-inch diameter iron-constantan
thermocouple. The experimental temperature plot for the pipe air is found in
figure A-2. The calculated pipe air velocities are listed in table A-1. These
flow calculations are all simplified in that one-dimensional flow is assumed
throughout, and no transient corrections were applied to the thermocouple
measurements. The calculated velocities represent the mean velocity in the
pipe.

In order to assess the validity of these calculations, velocity measurements
were taken at the pipe centerline during the test with a hot wire anemometer.
The sensor was a Thermo-Systems model 1210-20 hot film probe and the anemometer
was from a Thermo-Systems 1050-2C research system. The probe was calibrated
with a Thermo-Systems model 1125 calibrator. The calibrator gave the velocity
versus voltage curve shown in figure A-3. The experimental hot wire voltages
during the test were multiplied by a correction factor of $\sqrt{\Delta Tc/\Delta T}$ to get an
equivalent voltage to use in reading figure A-3. The temperature difference
between the sensor and the calibrator air is denoted by ΔTc, and ΔT represents
the difference between the sensor temperature and the measured temperature in
the air pipe. Both the calculated and measured pipe air velocities are plotted
in figure A-4. Capacitors were added to the oscillograph amplifier to damp
out high frequency noise from the hot-wire trace. Significant turbulent
fluctuations are still evident in the hot-wire trace typified in figure 8 of
the text. The voltage was averaged by eye at 1-second intervals for the data
reduction. Since the calculated velocities represent an average across the
pipe cross section while the measurements take the maximum velocity at the
pipe centerline, the measured velocities in figure A-4 were slightly higher
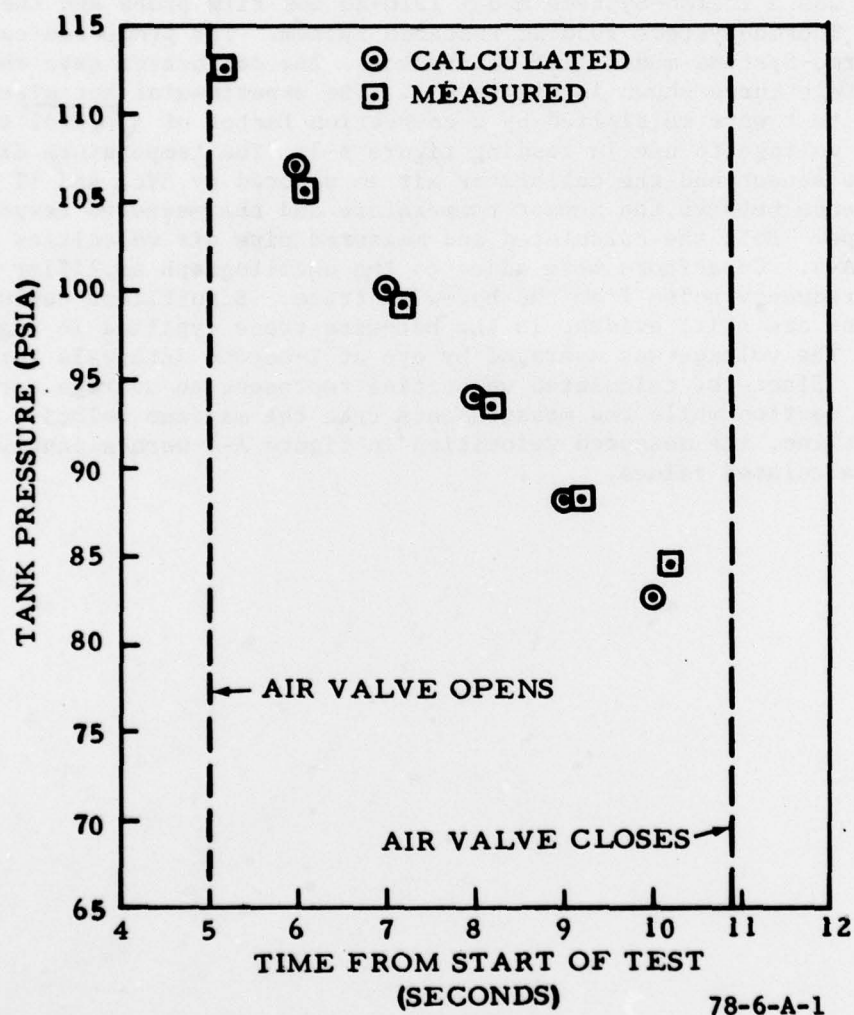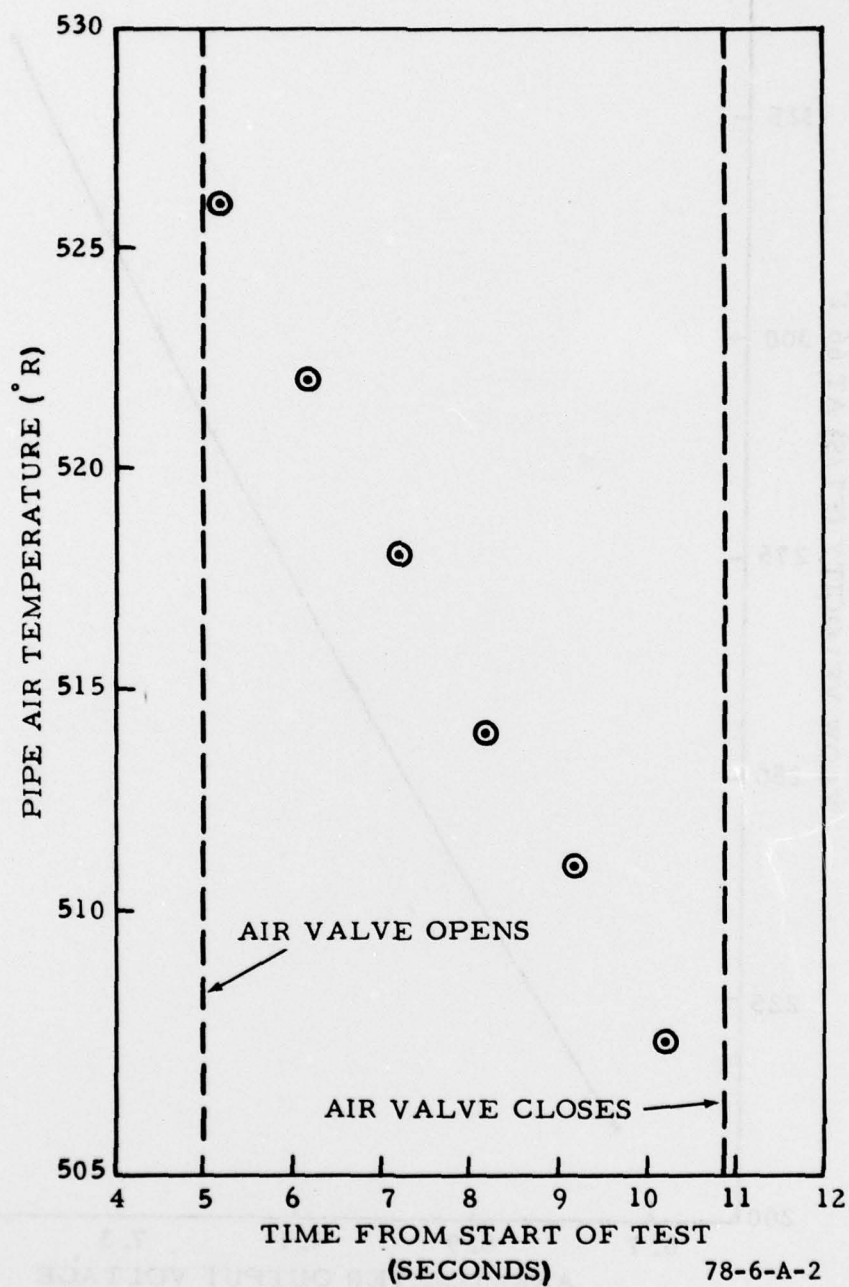than the calculated values.
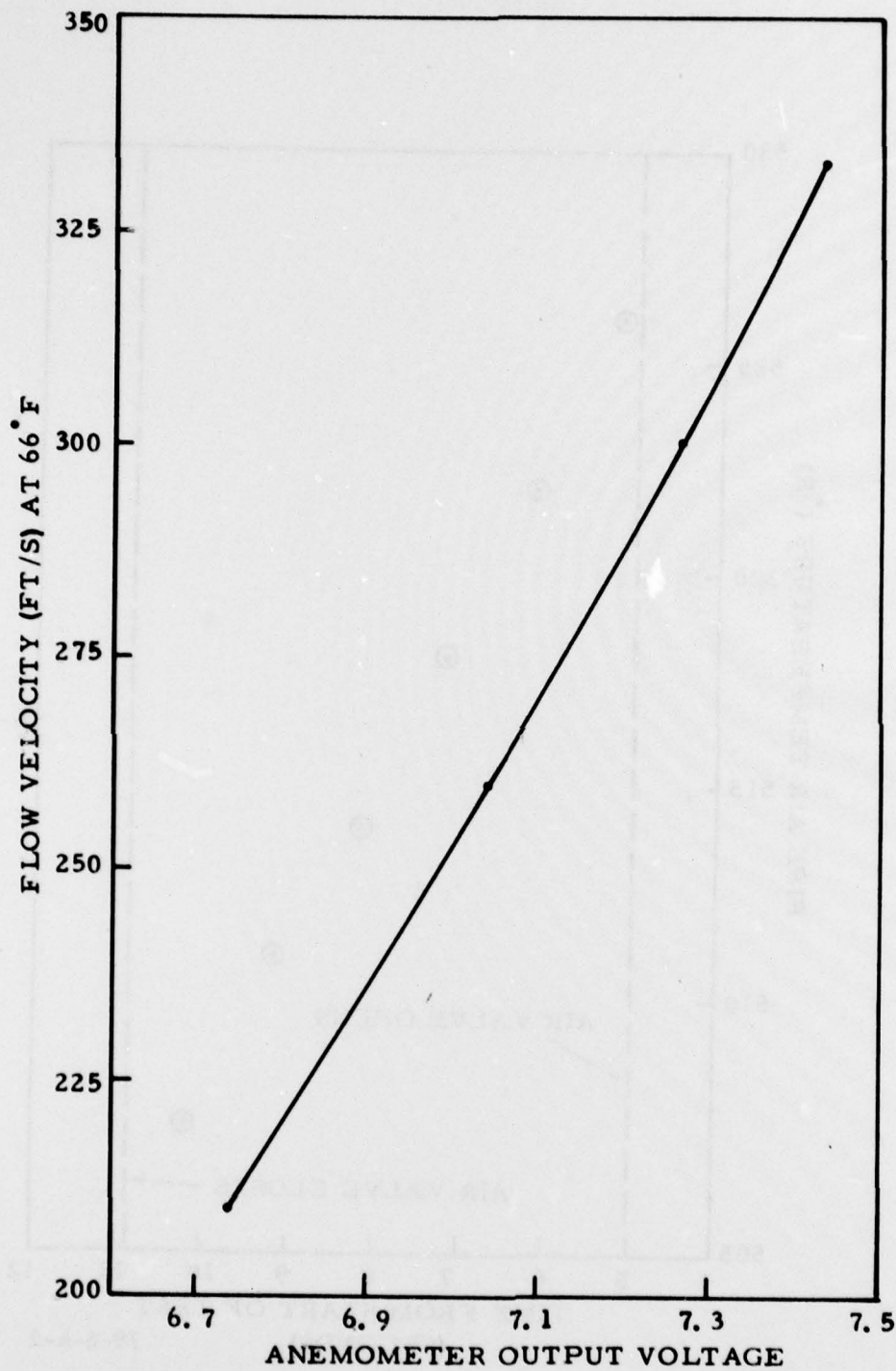
A-3

FIGURE A-1.   TANK PRESSURES

FIGURE A-2.   PIPE TEMPERATURES

A-5

FIGURE A-3.   HOT WIRE CALIBRATION
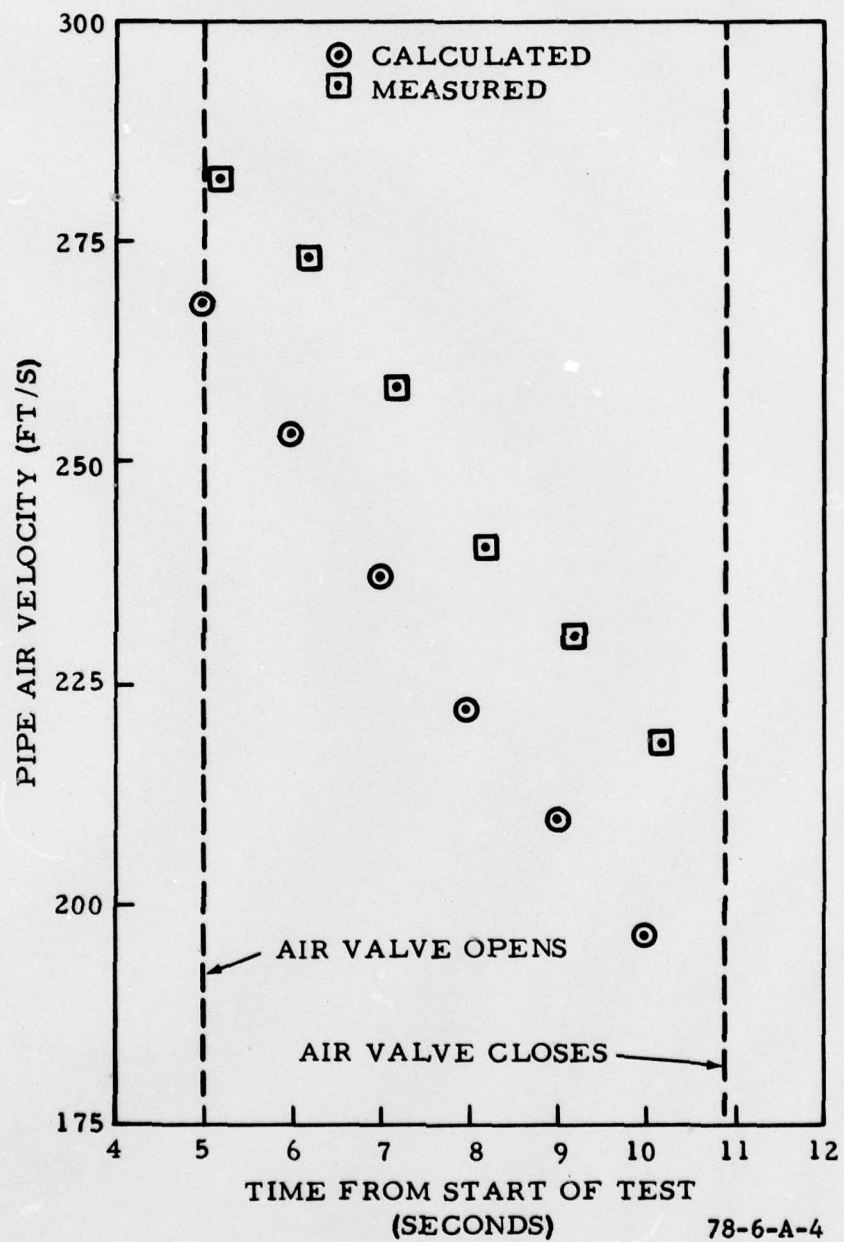
78-6-A-3

A-6

FIGURE A-4. PIPE AIR VELOCITY

A-7

APPENDIX B

DESIGN DETAILS

78-6-B-1

LEGEND

A.   Pump Assembly

B.   Pump reload solenoid valve, Skinner V52DA2100

C.   Propane solenoid valve, Skinner V52DB2022

D.   Air flow solenoid valve, Atkomatic No. 600 2-way

E.   Ignition transformer, Type 312-2AABC-202

F.   Timer (sequence), Mod. RC-1 industrial timer

G.   Annunciator lamps, Leecraft, 4 ea. D.C., 5 ea. A.C.

H.   Switch SPST toggle (3)

I.   Switch DPDT toggle

FIGURE B-1.   ELECTRONIC CONTROLS

1/4"

30° CHAMFER

15/64"

TAP FOR
5-40 4 PLACES

3/32"

1.000" ± .001"

8 5/8"

SECTIONAL VIEW OF CYLINDER

1/8"

1/4" NPT

.194"
.137"

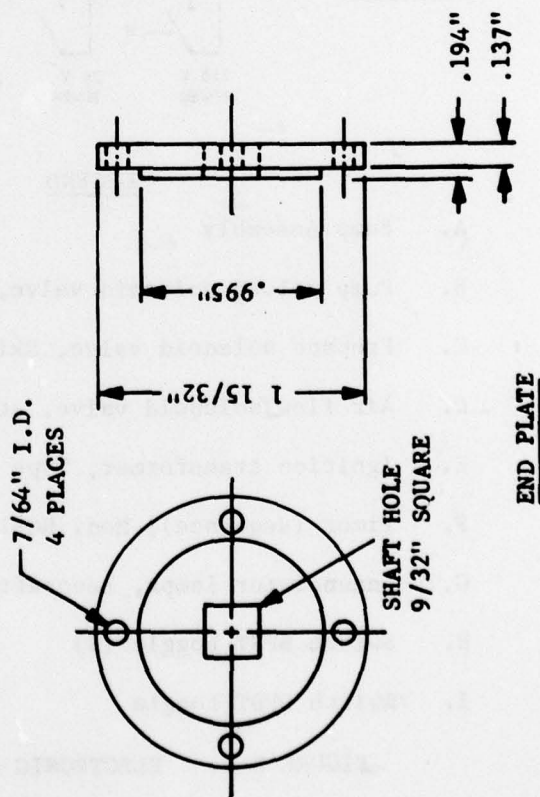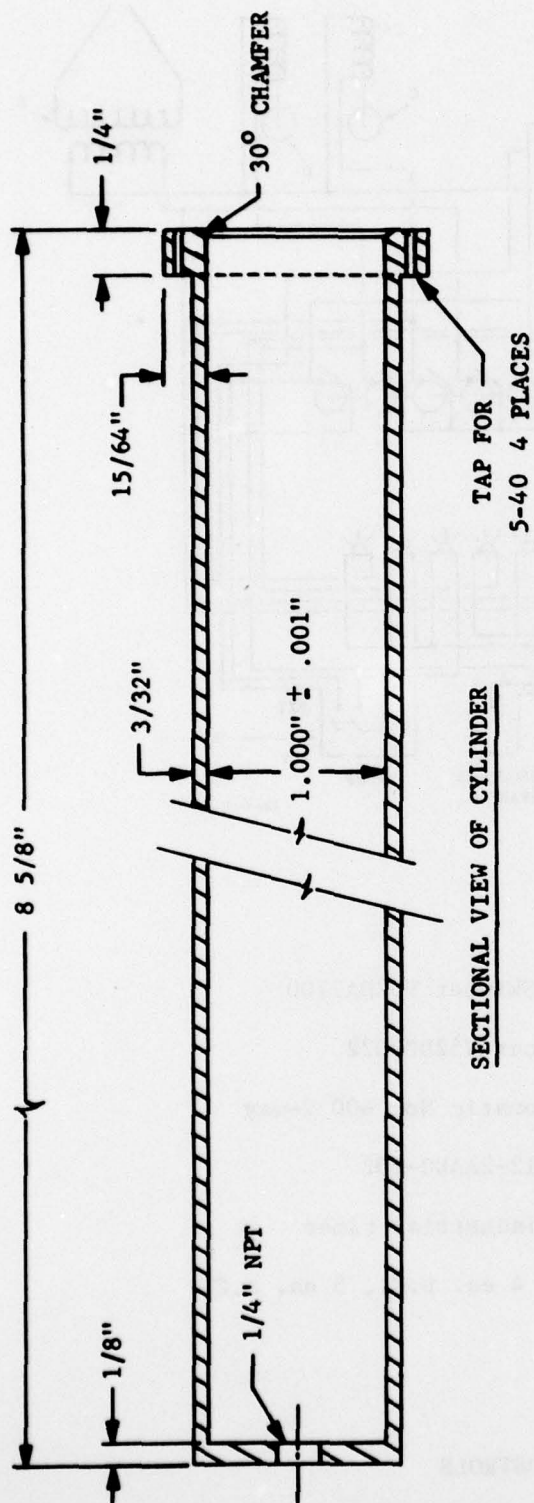.995"

1 15/32"

7/64" I.D.
4 PLACES

SHAFT HOLE
9/32" SQUARE

END PLATE

78-6-B-2

FIGURE B-2.   FUEL CYLINDER DETAIL

B-2

1/8" DIA. HOLE

1/4"

1/4" SQUARE
BAR STOCK

NOTE: PISTON GROOVED FOR 2 "O" RINGS
(PN AN 6227-15, MIL-P-5561C)

78-6-B-3

8 1/2"

1/4 - 20 THREAD
1/2" DEEP

1/8"

3/16"

SEE NOTE

1"

.123"

.766"

1/8"

3/16"

FIGURE B-3. FUEL PISTON DETAIL